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Mapping of the post-collisional cooling history of the Eastern Alps

STEFAN W. LUTH [1,*] & ERNST WILLINGSHOFER[1]

Key words: Eastern Alps, Tauern Window, geochronology, cooling, mapping, exhumation

ABSTRACT

We present a database of geochronological data documenting the post-collisional cooling history of the Eastern Alps. This data is presented as (a) georeferenced *isochrone maps based on Rb/Sr, K/Ar (biotite)* and *fission track (apatite, zircon)* dating portraying cooling from upper greenschist/amphibolite facies metamorphism (500–600 °C) to 110 °C, and (b) as *temperature maps* documenting key times (25, 20, 15, 10 Ma) in the cooling history of the Eastern Alps. These cooling maps facilitate detecting of cooling patterns and cooling rates which give insight into the underlying processes governing rock exhumation and cooling on a regional scale.

The compilation of available cooling-age data shows that the bulk of the Austroalpine units already cooled below 230 °C before the Paleocene. The onset of cooling of the Tauern Window (TW) was in the Oligocene-Early Miocene and was confined to the Penninic units, while in the Middle- to Late Miocene the surrounding Austroalpine units cooled together with the TW towards near surface conditions.

High cooling rates (50 °C/Ma) within the TW are recorded for the temperature interval of 375–230 °C and occurred from Early Miocene in the east to Middle Miocene in the west. Fast cooling post-dates rapid, isothermal exhumation of the TW but was coeval with the climax of lateral extrusion tectonics. The cooling maps also portray the diachronous character of cooling within the TW (earlier in the east by ca. 5 Ma), which is recognized within all isotope systems considered in this study.

Cooling in the western TW was controlled by activity along the Brenner normal fault as shown by gradually decreasing ages towards the Brenner Line. Cooling ages also decrease towards the E–W striking structural axis of the TW, indicating a thermal dome geometry. Both cooling trends and the timing of the highest cooling rates reveal a strong interplay between E–W extension and N–S orientated shortening during exhumation of the TW.

Introduction

The European Alps are one of the most intensively investigated orogens on earth. However, many questions remain, particularly in the Eastern Alps, such as the exact timing of deformation, metamorphism and exhumation of rocks and their related feedback loops with deep (mantle) as well as surface processes.

Many conclusions in the context of mountain building have been derived in the past with the help of geobarometry, geothermometry, and geochronology. The latter is useful to constrain the timing of metamorphic and deformation events under certain temperature and pressure conditions within evolving orogens. Geochronological data from the Eastern Alps is abundant and underpins many findings throughout the last decades. For example, the Eastern Alps bear evidence for two independent collisional events in the Cretaceous and the Paleogene, respectively (e.g. Neubauer et al. 2000 and references therein) or the temporal variations of peak metamorphic conditions (Inger & Cliff 1994; Hoinkes G. 1999; Neubauer et al. 2000). The wide spread in recorded ages, both, in time and space, in combination with the complex Alpine history has given rise to different interpretations of their meaning (e.g. crystallization, metamorphism, exhumation). A review of geochronological data in a regional framework can be valuable in deciphering orogen-scale trends, which help to better constrain processes at work and to separate local from regional effects.

Following up on the reviews of e.g. Frank et al. (1987a), Thöni, (1999) and Hoinkes et al. (1999), we present updated and geo-referenced compilations of isotope data for the Eastern Alps.

The presented work aims to map the post-collisional cooling history of the entire Eastern Alps by compiling available cooling ages in one single database. From this database we can extract thematic maps regarding the cooling history by using GIS mapping tools. These cooling maps can be used to gain

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insight into regional cooling trends, cooling rates, and their relation with the tectonics, such as the formation of the Tauern Window (TW), the distribution of north-south shortening due to indentation, or the onset of lateral extrusion. Furthermore, the presented database also highlights regions of poor data coverage and, hence, may be of importance for the planning of future dating projects. The database will be updated regularly and can be accessed via the internet (http://www.geo.vu.nl/~wile/).

Geological Setting

The structure of the Eastern Alps is that of a collisional orogenic belt with the continental Austroalpine (AA) unit as highest tectonic unit overlying the Penninic ("Alpine Tethys") suture and the continental units, including their sedimentary cover of European affinity (i.e. Sub-Penninic sensu Schmid et al. 2004) in lowest structural position (Figs. 1a–b). Multiply deformed Austroalpine basement and cover units of Apulian origin are most abundant in the Eastern Alps and their internal structure and last metamorphic overprint is related to Cretaceous stacking of tectonic units following the consumption of the Triassic Meliata ocean farther east (Neubauer et al. 2000 and references therein). The Penninic suture and the Sub-Penninic units are exposed along the central axis of the Eastern Alps within tectonic windows such as the Engadin-, Tauern- and Rechnitz Windows.

They contain remnants of the Penninc oceanic crust, (para) autochthonous, highly metamorphosed cover units of the European continental shelf (Lower Schieferhülle), and allochthonous metasediments, derived from the Penninic Ocean (Upper Schieferhülle). The ophiolites belong to the Jurassic, Alpine Tethys (Penninic Ocean), which separated European from Apulian paleogeographic domains (Frisch 1979; Oberhauser 1995; Schmid et al. 2003). Subduction of this ocean commenced during the late Cretaceous and lasted until the Eocene (Frisch, 1979).

The core of the TW exposes pre-Variscan metamorphic basement and Variscan granitoids, the Zentralgneiss, in a series of domes (Zimmermann 1994; Oberhänsli & Goffé 2004). The domes form the core of a large anticline with an axis parallel to the window's strike as a result of syn- and post collisional shortening coeval with orogen-parallel extension (Lammerer and Weger, 1998).

The Periadriatic Fault separates the AA units from the Southern Alps, a Miocene, south vergent fold and thrust belt of Apulian origin (Castellarin et al. 1992) (Fig. 1). Slip along this fault was right-lateral with a minor (few kilometers) north-side up component during the late Oligocene and Miocene (Ratschbacher et al. 1991; Mancktelow 1995).

Several Tertiary plutons are located along or in the vicinity of the Periadriatic line, such as the Rensen and Rieserferner plutons. Rb/Sr whole rock dating on these granodiorites and tonalites reveals Oligocene ages and geochemical analyses demonstrate a source at the base of thickened crust (Borsi et al. 1978b).

Metamorphism in the Eastern Alps

Austroalpine Units

The AA units are characterized by widespread Cretaceous (Eo-Alpine) metamorphism and a weak post-Cretaceous thermal overprint, which is largely restricted to the vicinity of the TW (e.g. Thöni 1999; Hoinkes et al. 1999).

In general, the grade of the eo-Alpine metamorphism increases from north to south from sub-greenschist to ultra-high pressure conditions (Hoinkes et al. 1999; Oberhänsli & Goffé 2004; Janak et al. 2004). The southern limit of the Alpine greenschist to lower amphibolite metamorphic overprint, as indicated by incomplete resetting of the Rb-Sr white mica system (Borsi 1978) within AA units, coincides with the Defereggen-Antholz-Vals (DAV) Line (Fig. 2b) (Hoinkes et al. 1999 and references therein; Most, 2003). North of the DAV age data within the AA units are only slightly older than those from the TW. In contrast, zircon Fission Track (FT) data to the south of the DAV exclusively record pre-Miocene cooling (Stöckhert et al. 1999; Steenken et al. 2002).

The Paleogene thermal overprint within AA units close to the northeastern corner of the TW is related to thrusting within the lowermost AA units (Liu et al. 2001).

Penninic Units

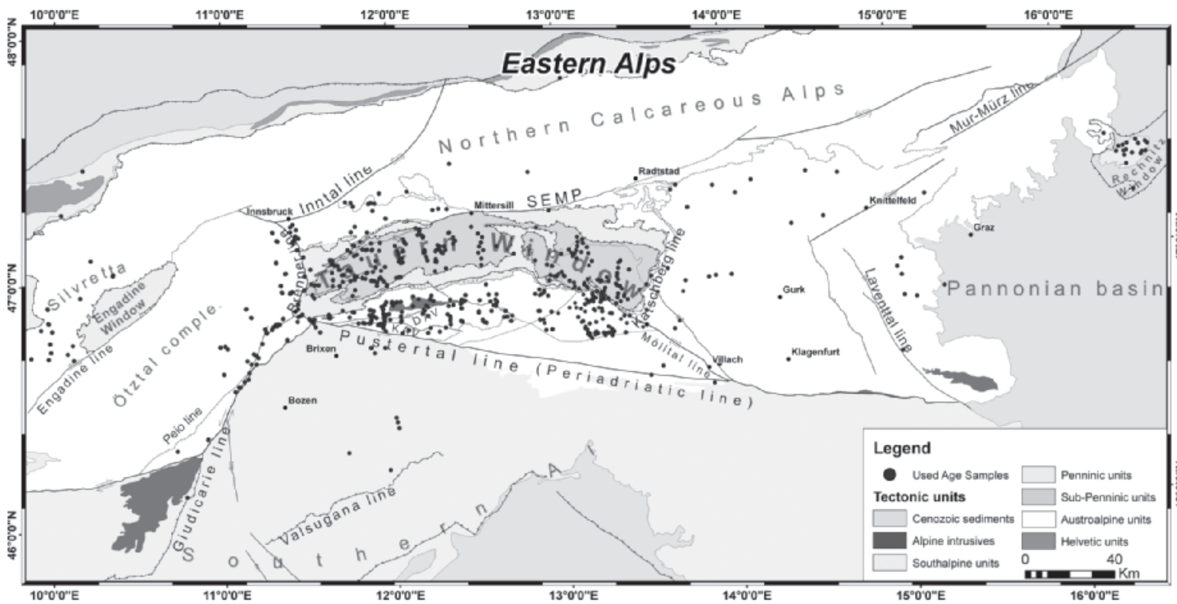
The metamorphic grade within the Penninic units ranges from eclogite- to greenschist facies. In general, PT-loops derived from different areas in the Eastern Alps show a retrograde path from eclogite facies metamorphic conditions followed by blueschist and amphibolite/greenschist facies metamorphism (Hoinkes et al. 1999).

Eclogite facies metamorphic rocks are restricted to a relatively small strip in the central southern TW (Eclogite Zone) (Fig. 2). According to Frank (1987) the eclogites first cooled to blueschist facies conditions followed by reheating again to 500–600 °C and pressures between 5 and 7 kbar. Further cooling to 375–400 °C and 2–4 kbar took place along similar paths for all Penninic units (Holland 1979).

Timing of eclogitization is speculative, but if dating of the subsequent blueschist event is correct, then the eclogites are of pre-Oligocene age. Eclogite formation occurred under peak pressures of 20–25 kbar and temperatures between 580–650 °C (Holland 1979; Frank 1987; Kurz et al. 1998). These conditions are equivalent to depths of about 60–90 km and were characterized by a very low geothermal gradient of 7–9 °C/km typical for subduction zones (Fig. 2a).

K/Ar white mica ages from the southern border of the central TW range between 34 and 30 Ma and are interpreted as crystallization ages related to blueschist metamorphism (Lambert 1970; Cliff et al. 1985; Zimmermann 1994). Data compiled by Frank et al. (1987) suggest that blueschist formation occurred at temperatures between 400 and 500 °C and pressures around 9 kbar in the TW. The blueschist metamorphic event

a



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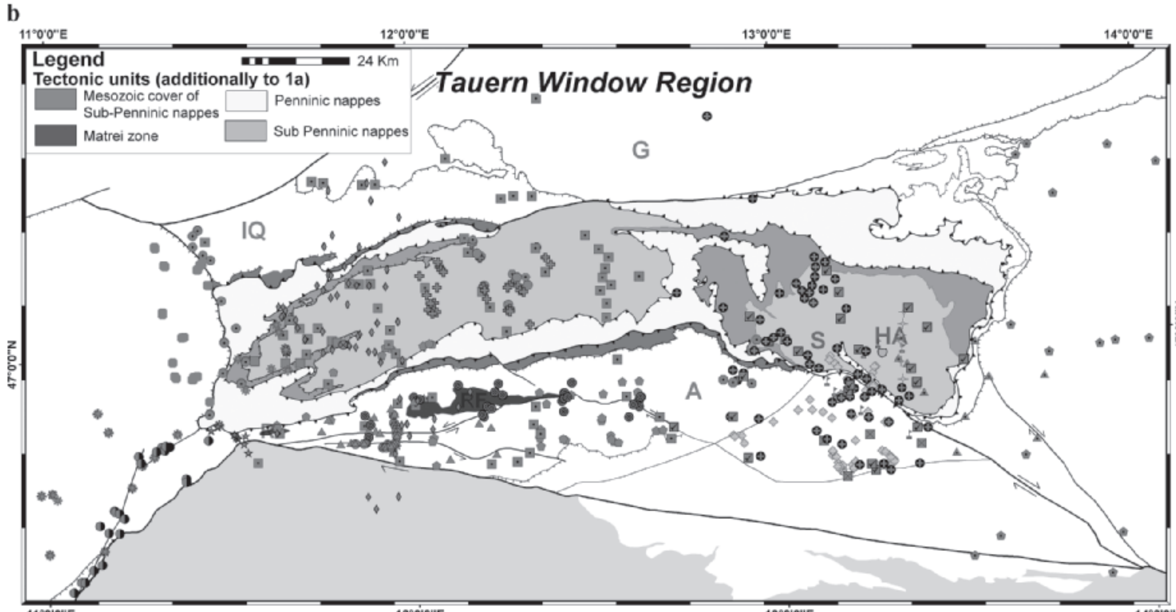
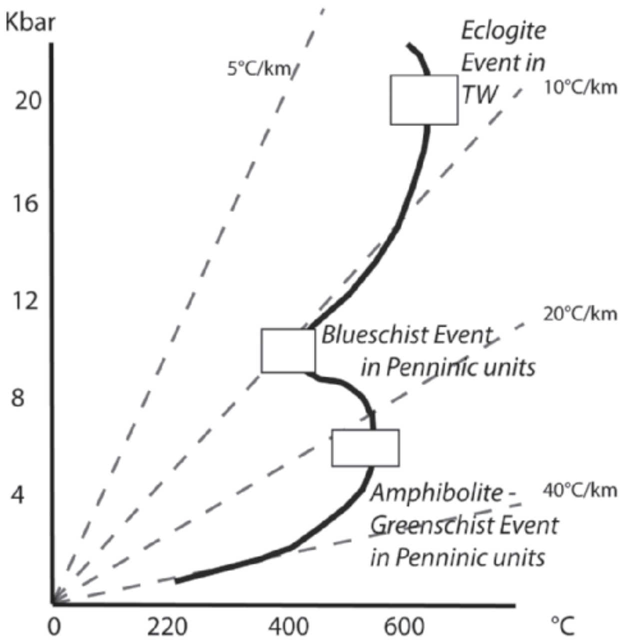


Symbol	Author	System
●	Besang et al., 1968	Rb/Sr, K/Ar, biotite
■	von Blackenburg et al., 1989	Rb/Sr, K/Ar, biotite
▲	Borsi et al., 1973	Rb/Sr, biotite
⬟	Borsi, 1977	Rb/Sr, biotite
⬢	Borsi, 1978	Rb/Sr, biotite
⊠	Brewer & Jenkins, 1969	K/Ar, biotite
☑	Dunkl et al., 2003	ZFT, AFT
✧	Foeken et al., 2007	AFT
■	Fügenschuh et al., 2000	ZFT, AFT
⊙	Fügenschuh et al., 1997	ZFT, AFT
▣	Grundmann & Morteani, 1985	AFT
▲	Hawkesworth, 1976	Rb/Sr, biotite
⬟	Hejl, 1997	AFT
♪	Hoke, 1990	K/Ar, biotite

Symbol	Author	System
⊙	Jäger et al., 1969	Rb/Sr, biotite
◉	Lambert, 1970	K/Ar, biotite
★	Mancktelow et al., 2001	ZFT, AFT
♦	Most, 2003	K/Ar, biotite, ZFT, AFT
⛉	Oxburgh et al., 1966	K/Ar, biotite
✚	Raith et al., 1978	K/Ar, biotite
✳	Satir, 1975	Rb/Sr, K/Ar, biotite
⊗	Satir & Morteani, 1982	Rb/Sr, biotite
⊕	Staufenberg, 1987	AFT
◎	Steenken et al., 2002	K/Ar, biotite, ZFT, AFT
◬	Stöckhert et al., 1999	ZFT
◐	Viola et al., 2001	ZFT, AFT
◇	Wölfler, 2008	ZFT, AFT
⊕	Zattin et al., 2006	AFT

Fig. 1. a) Simplified tectonic map of the Eastern Alps based on Bigi et al. (1990–92) and Egger et al. (1999). The dots represent the sample locations used in this study. Abbreviations, DAV: Defferegggen-Antholz-Vals Line, KAV: Kalkstein-Vallarga Line, SEMP: Salzach–Ennstal–Mariazell–Puchberg Line. b) Overview of the distribution of sample locations in the Tauern Window region of which geochronological data have been used in this study. Different symbols refer to previous studies as shown in the table. Abbreviations, R: Rensen pluton, RF: Rieserferner pluton, IQ: Innsbruck Quartzphyllite, G: Greywacke zone, A: Altkristallin, S: Sonnblick dome, HA: Hochalm dome.

a



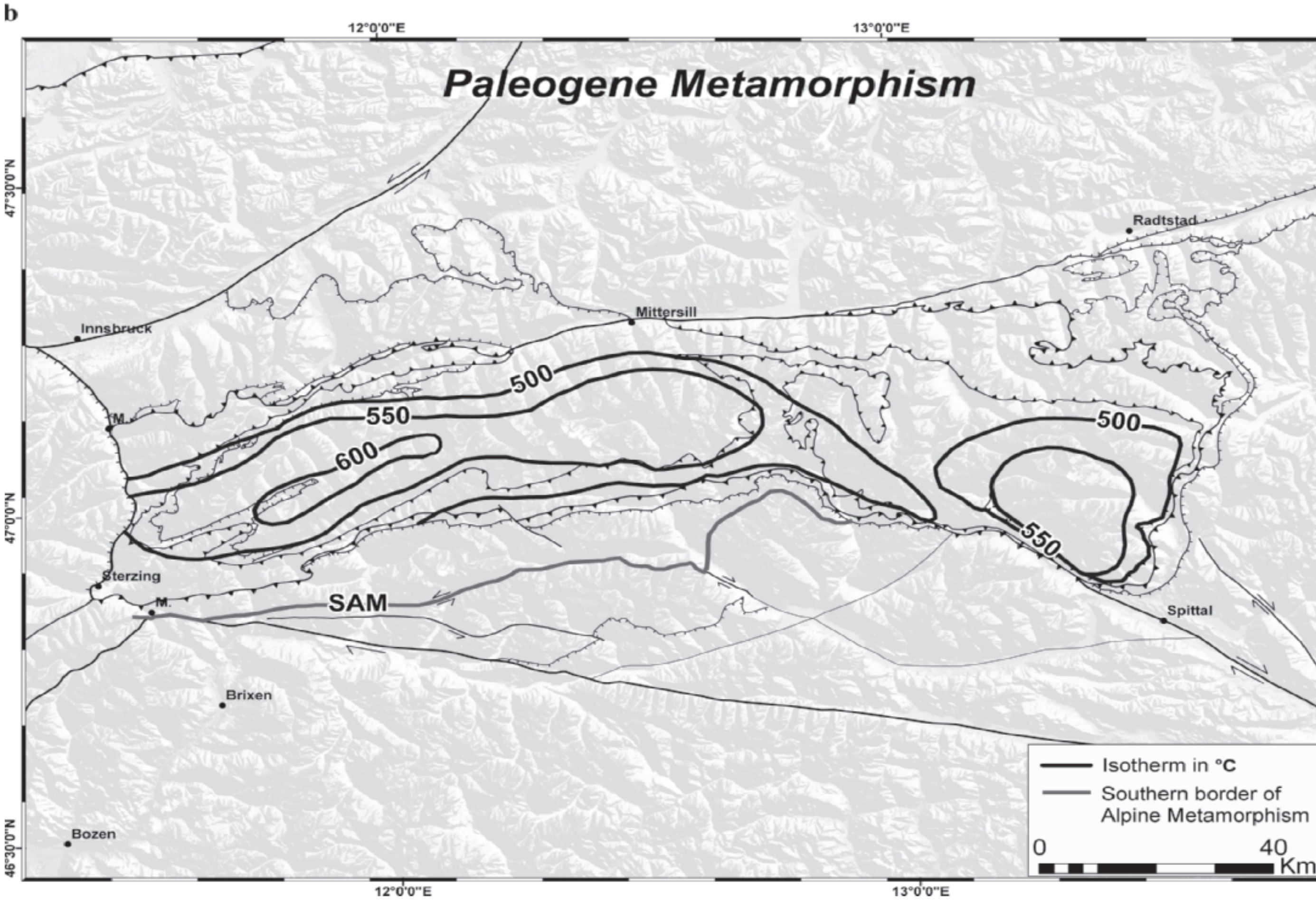
represents a stage of exhumation from ~80 km to ~35 km (e.g. Kurz et al. 1998).

Within the Rechnitz Window remnants of a high-pressure/low-temperature event are found within ophiolitic sequences and yielded metamorphic conditions of 330–370 °C and minimum pressures of 6–8 kbar (Koller 1985). There is no correlation of the blueschist facies metamorphism throughout the Penninic realm due to a lack of reliable age dating.

Within most of the Penninic units, Oligocene greenschist to amphibolite facies metamorphism led to penetrative deformation of rocks and the (re)crystallization of mineral assemblages of which white micas from the eastern TW have been

Fig. 2. a) Generalized pressure-temperature loops of the Penninic units at different locations within the Eastern Alps after Kurz et al. (1998) and Hoinkes et al. (1999). TW: Tauern Window. Dashed lines show different isotherms. b) Map showing Paleogene peak temperatures in the Eastern Alps. After Oberhänsli & Goffé (2004).

b



dated between 30 and 28 Ma (Inger & Cliff 1994; Thöni 1999). Peak temperatures of 550 to 600 °C under pressure conditions of 5–7 kbar reflect a geothermal gradient of 20–35 °C/km (Inger & Cliff 1994; Kurz et al. 1998; Hoinkes et al. 1999; Thöni 1999). The timing of subsequent cooling is not well constrained since Rb/Sr white mica data from the western TW yielded ages as young as 16 Ma (Von Blanckenburg et al. 1989). Whether these young ages reflect crystallization, cooling, or partial isotope resetting due to ongoing deformation, is still debated (Cliff et al. 1985; Von Blanckenburg et al. 1989; Hoinkes et al. 1999; Thöni 1999). However, lower temperature isotope systems reveal a clear westward younging of cooling ages, which possibly existed at higher temperatures as well. Post-metamorphic deformation resulted in folding of the Oligocene isograds along the central axis in the western TW and the Sonnblick and Hochalm domes in the eastern TW as well as the formation of normal faults bounding the TW in the west (Brenner fault) and the east (Katschberg fault). A distinct break in metamorphic grade across both faults affirm their normal fault kinematics (Behrmann 1988; Selverstone 1988; Genser & Neubauer 1989; Fügenschuh et al. 1997).

Data Compilation

The presented cooling maps are based on *c.* 600 published age measurements derived from Rb/Sr, K/Ar (biotite) and fission track (zircon, apatite) dating, portraying a temperature range of 375–110 °C (Table 1). The obtained data were published between 1968 and 2008 and are interpreted as cooling ages. The data covers the entire Eastern Alps from the Silvretta/Engadine region in the west to the Rechnitz Window in the east, but are concentrated in several clusters mainly distributed within the TW region (Fig. 1a & b). For a complete reference list for the database, see Figure 1b.

Construction of the Cooling Maps

All dating locations have been plotted on a georeferenced tectonic base-map with a Europe Lambert Conformal Conic projection, which is a combination of the "Structural model of Italy" 1:500.000 (Bigi et al. 1990–92) and the "Geologische Übersichtskarte der Republik Österreich", scale 1:1.500.000 (Egger et al. 1999). Georeferencing and plotting of data has been done with ArcGIS 9® software.

The construction of the cooling maps through time is performed in two steps:

1) The data were categorized after closure temperature for producing three different age contoured *"isochrone maps"* (Fig. 3a–c). The pertinent temperatures to these maps are: 375 °C (K/Ar and Rb/Sr biotite), 230 °C (zircon-FT), and 110 °C (apatite-FT) (Tab. 1). Contouring of the ages was carried out after interpolation of separate data clusters by the nearest neighbour technique. The result was compared with and partly adjusted by manual contouring to minimize or remove uncertainties owing to data scarcity and to derive at robust interpretations.
2) In order to visualize temperature at certain time periods, *"temperature maps"* were constructed (Fig. 4a–d). The time periods cover the cooling history between 25 and 10 Ma and are identical to the isochrone age intervals on the time maps. Therefore, temperature contours (isotherms) can be deduced from isochrones as well. For example, the *15 Ma temperature map* contains 110 °C isotherms, which are identical to the 15 Ma isochrones on the *110 °C isochrone map*. The combination of isotherms and the closure temperatures of samples belonging to the same age were used as input for a nearest neighbour interpolation of the temperature. For the 15 and 10 Ma temperature maps, younger ages were also included to allow distinction between samples that had already cooled to 110 °C and those that were still hotter as they show ages younger than 10 Ma. In order to visualize this difference, the younger samples were assigned a few tens of degrees above the high temperature limit of the partial annealing zone for the apatite-FT system on these particular maps.

Assumptions, Uncertainties and Simplifications

Since the Rb/Sr, Ar/Ar and K/Ar systems in biotite record lower than peak metamorphic temperatures, which range between 500–650 °C in the Tauern Window, we apply the closure temperature concept and assume that the bulk of the data reflect post-metamorphic cooling. What is considered as closure temperatures are actually averaged temperature ranges. Especially for fission track analysis there is no specific closure temperature but a partial annealing zone defined by a temperature range in which early formed tracks can (partially) anneal and the track lengths can be reduced. Hence, only fission tracks with long track lengths, indicating rapid cooling, are consistent with

Table 1. Closure and partial annealing zone temperatures for the used thermochronometers.

Isotope system	Mineral	Used closure temperature (°C)	Closure temperature range (°C)	References
$^{40}Ar/^{39}Ar$ $^{40}K/^{39}Ar$	Biotite	375	300–400	(Grove & Harrison 1996) (Villa 1998)
	Muscovite		375–430	(Kirschner et al. 1996) (Hames & Bowring 1994)
$^{87}Rb/^{86}Sr$	Biotite	375	250–350	(Jäger et al. 1969)
			400	(Del Moro et al. 1982)
	White mica		450–550	(Jäger et al. 1969)
				(Purdy & Jäger 1976)
Fission track	Zircon	230	300–180	(Hurford & Green 1983; Zaun & Wagner 1985)
	Apatite	110	90–120	(Green et al. 1986; Gallagher et al. 1998)

the closure temperature concept. However, with respect to the rapid exhumation history of the Alps from the Oligocene onward, average temperatures seem a reasonable approximation since the variation of ages within the partial annealing zone might be of minor importance (Tab.1). The temperature range of the partial annealing zone for Apatite FT is in the order of 120–60 °C, while that for Zircon FT is 300–180 °C (see Tab. 1 for references).

The interpretation of muscovite and phengite ages as cooling ages is still controversial since (re)crystallization of these minerals can occur even below the closure temperature (e.g. (Glasmacher et al. 2003). Some K/Ar muscovite ages in the central TW are younger than nearby K/Ar biotite ages, although the Tc of the former is generally regarded as higher (Raith et al. 1978). Therefore, white mica ages are not shown on a separate time map, but can be used to support interpretations of the *Biotite 375 °C isochrone map* since their closure temperature ranges have some overlap (Tab. 1). Additionally, Rb/Sr white mica ages are regarded as crystallization ages and are, therefore, not considered in this compilation.

In this study we applied a simple filter excluding apatite fission track data from altitudes higher than 2000 m and lower than 1000 m in order to avoid topography-induced complexities of the cooling history, which are not representative for the regional cooling of the Eastern Alps (compare Figs. 3c and d). The chosen elevation range is based on the large amount of available data within this bracket (see histogram in Fig. 3d). Ideally, since positive age vs. altitude relationships are only observed in some sub-regions of the Eastern Alps, corrections for topography should be applied for those sub-areas separately.

Many publications lack accurate coordinates of sample locations. Hence, we applied simple scanning and georeferencing of maps and sketches and adjusted the geographical projections to our base map. Although some maps have untraceable projections and/or oversimplified sketches have been used, the maximum deviation of the plotted locations does not exceed 100 meters and is therefore a minor source of uncertainty.

Cooling Maps

In the following sections the compiled cooling maps will be described starting with the time maps for different isotope systems followed by the temperature maps, which portray regional cooling through time. Isolines with the same time are referred to as "time lines" or "isochrones". References to the underlying data are summarized in Fig. 1b and will not be repeated in the context of the description of the cooling maps.

375 °C Isochrone Map

AustroalpineUnits

The majority of the Austroalpine units cooled below 375 °C before Cenozoic times. However, the unit between the TW and the Periadriatic Line behaved differently and can be divided into a southern unit containing pre-Cenozoic ages and a northern unit, which shows a remarkable decrease of ages toward the TW on the 375 °C map (Fig. 3a) as well as on the 230 °C map (Fig. 3b). Both units are separated by the DAV (for location see Fig. 1), which coincides with the 65 and 35 Ma isochrones. In the area between the south-western corner of the TW and the tip of the Southalpine indenter, isochrone-lines trend parallel to the TW and the Brenner fault, respectively. Of particular note is the considerable north-directed age drop from 65 to 20 Ma within ~10 km distance in this zone.

Penninic Units

The youngest ages within the TW are found in its south-western corner, ranging between 15 and 12 Ma (Fig. 3a). From this location, ages gradually increase towards the northeast. The 20 Ma isochrone surrounds the western TW tracing the Brenner Line in the west and gradually closes along the central axis towards the east. Contouring along the TW's northern boundary is difficult due to lack of data. The higher temperatures there are indirectly deduced, based on relatively old zircon FT ages (Fig. 3b). Two trends appear clearly from contouring in the western TW: (1) A younging trend toward the central ENE–WSW trending structural axis of the window, which starts in the Austroalpine units with the DAV as southern limit. (2) A gradual WSW directed younging trend towards the Brenner Line, across which a distinct age break is observed.

The data from the eastern TW, though limited in amount, suggest earlier cooling than in the western TW, which is supported by K/Ar and Ar/Ar muscovite ages ranging between 30 and 20 Ma in the north-eastern TW (Liu et al. 2001), and between 27–18 Ma in the south-eastern TW (Cliff et al. 1985). Additionally, considering the confinement of Oligocene peak metamorphic conditions within the TW it is expected that the isochrones will largely follow the outline of the TW.

230 °C Isochrone Map

Austroalpine units

Parts of the Austroalpine unit between the TW and the Rechnitz Window referred to as "cold spots" by (Hejl 1997), cooled below 230 °C before Cenozoic times. More cold spots have been found in the Ötztal-Stubai basement complex, the north-eastern part of the Innsbruck Quartzphyllite, the Greywacke zone, and AA basement units north of the Periadriatic Line.

Similar to the 375 °C isochrone map, a high gradient of northward younging from 80 Ma just a few kilometers south of the Periadriatic line to 13 Ma adjacent to the TW is observed north of the Southalpine indentor. Further east, the isochrones are parallel to the DAV.

Penninic units

The south-western corner of the TW cooled through 230 °C between 15 and 12 Ma, similar to the 375 °C map indicating high cooling rates (50 °C/Ma).

In contrast, a gradual westward younging within the western TW is not well expressed, which could be due to the lack of data in the central TW. The eastern Tauern Window is characterized by 19–16 Ma zircon FT ages. Due to the lack of zircon FT ages in the central TW it is not possible to reconcile whether cooling was progressive from east to west or a separation into domains with different cooling ages. A trend towards younger ages from the window's northern border (20 Ma) towards the central axis (12 Ma) is observed within the western TW. North of the DAV ages drop from 25 to 12 Ma in northerly direction.

Cooling below 230 °C in the Rechnitz Window took place between 19 and 14 Ma. The Rechnitz thermal event also led to rejuvenation of the surrounding AA unit as indicated by a 22 Ma age measurement by Dunkl & Demeny (1997).

Southern Alps

Within the Southalpine Basement units zircon fission track ages range between 225 and 213 Ma. Only ages between 81 and 24 Ma from the Permian Brixen pluton close to the Periadriatic Line record Alpine resetting (Mancktelow et al. 2001; Viola et al. 2001).

110 °C Isochrone Map

Apatite fission track (AFT) data are displayed in figure 3c utilizing all of the compiled data. In figure 3d, only data within a selected altitude range (1000–2000 m) have been used in order to avoid dubious interpretations due to topographic affects.

Austroalpine Units

Within the Silvretta basement units west of the Engadine Window, AFT-ages vary from 31 Ma in the east and south to 14 Ma towards the southwest.

In the Ötztal-Stubai area AFT-ages get successively younger approaching the Brenner Line in a SE to E direction. The northwestern part of the Innsbruck Quartzphyllite region cooled below 110 °C not before 15 Ma and, therefore, differs from the bulk of the TW's northern surroundings; in the Greywacke zone AFT ages increase northwards to 60 Ma.

Most ages taken from the Austroalpine units between the Periadriatic line and the TW fluctuate between 20 and 10 Ma and increase slightly towards the southeast, similar to the 375 °C and the 230 °C isochrone maps. The irregular curved shape of isochrones resulting in crossing major tectonic boundaries, such as the DAV (compare Fig. 3c and Fig. 3d), is mainly due to topographic effects. Notice the remarkable difference in timing of cooling at the Brenner- and Katschberg Lines.

Penninic Units

Within the TW, cooling below 110 °C started in the east as early as 20 Ma ago and propagated westwards from that time on. No AFT data are available from the north-eastern TW, which has been contoured by extrapolation of ages from farther south. Somewhat younger ages (15–10 Ma) in the south-eastern corner of the TW may be disturbed by high thermal anomalies associated with the Mölltal fault (Dunkl et al. 2003; Wölfler 2008).

Towards the western part of the eastern TW the age variation becomes larger (16–6 Ma) and practically all AFT-ages within the central and western TW fall between 10 and 5 Ma. Here, westward younging is only limited to the Brenner Line region where ages are as young as 9–4 Ma. A younging trend towards the central axis of the TW is not well constrained. The disturbance of the isochrons may partly be due to the age/elevation correlation.

Only two AFT ages have been found in the Rechnitz Window and are dated at 10 and 7 Ma, indicating coeval cooling within the TW and Rechnitz Window below 110 °C at that time.

Southern Alps

A few ages from the Southern Alps can be interpreted only very broadly and isochrones are restricted to the Brixen pluton, which cooled below 110 °C in the Early Miocene, while further south cooling of the Southalpine Basement through 110 °C was not before 15–11 Ma. The general trend, though poorly constrained, is a north-south younging to 10 Ma near the south-vergent Valsugana thrust (Fig. 1a).

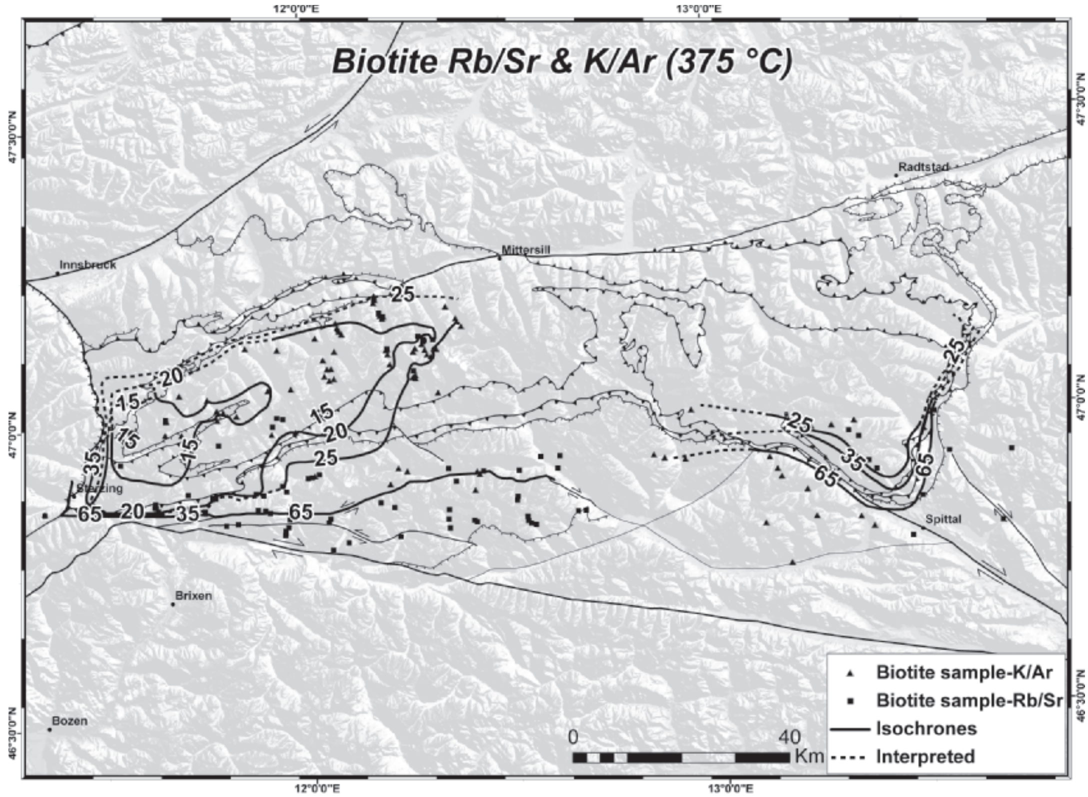
Temperature Maps

The four temperature maps (Figs. 4a–d) are interpolations derived from the isochron maps and contain the same underlying information, albeit visualizing temperature at a certain time. On a single temperature map, information is combined from all the used dating systems and used as additional control on the internal consistency of the isochron maps. This improved the contouring particularly in areas with scarce data coverage and thus, both map types are complimentary.

In the following section, the temperature maps for the time interval from 25 to 10 Ma will be briefly discussed. At 25 Ma (Fig. 4a) temperatures in the entire western and marginal parts of the eastern TW exceeded 375 °C. The "hot cells" of the western and eastern TW, exhibiting the geometry of "elongate thermal domes" are separated by a cooler region in the central TW. The significance of this temperature distribution, however, remains uncertain since few cooling age data are available from the central TW.

At 20 Ma (Fig. 4b) the eastern TW had cooled almost entirely below 200 °C with the exception of the Sonnblick and Hochhalm domes (for location see Fig. 1b).

a



b

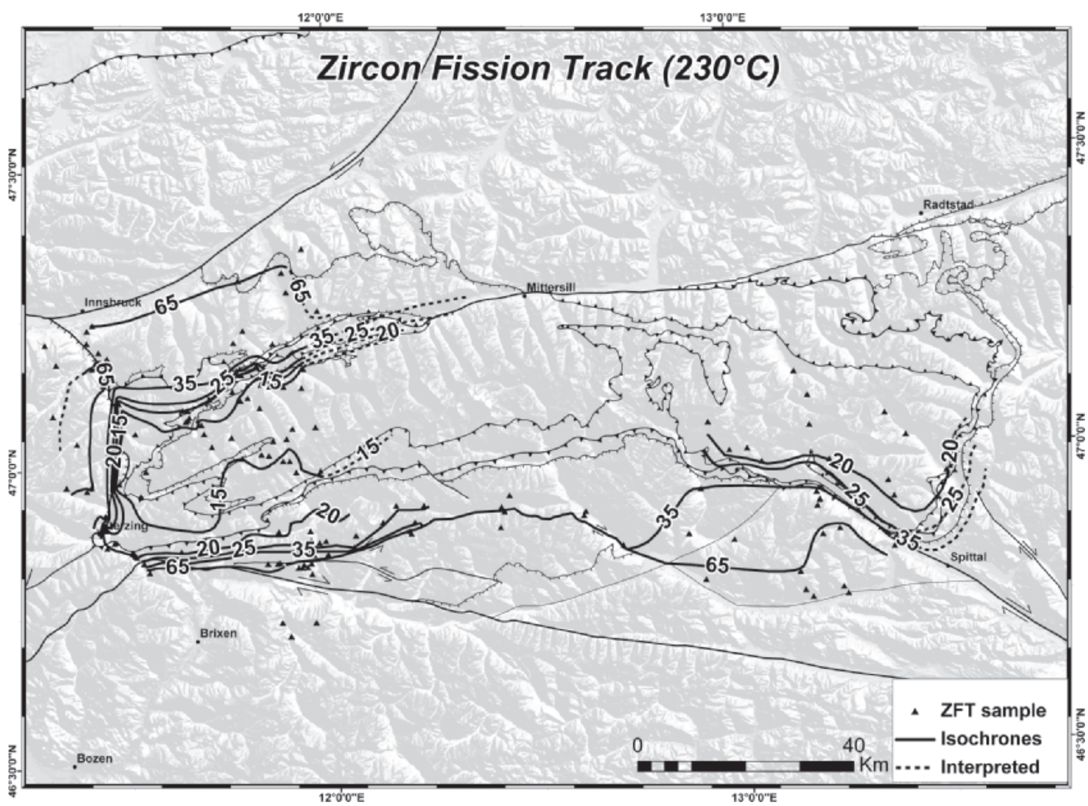
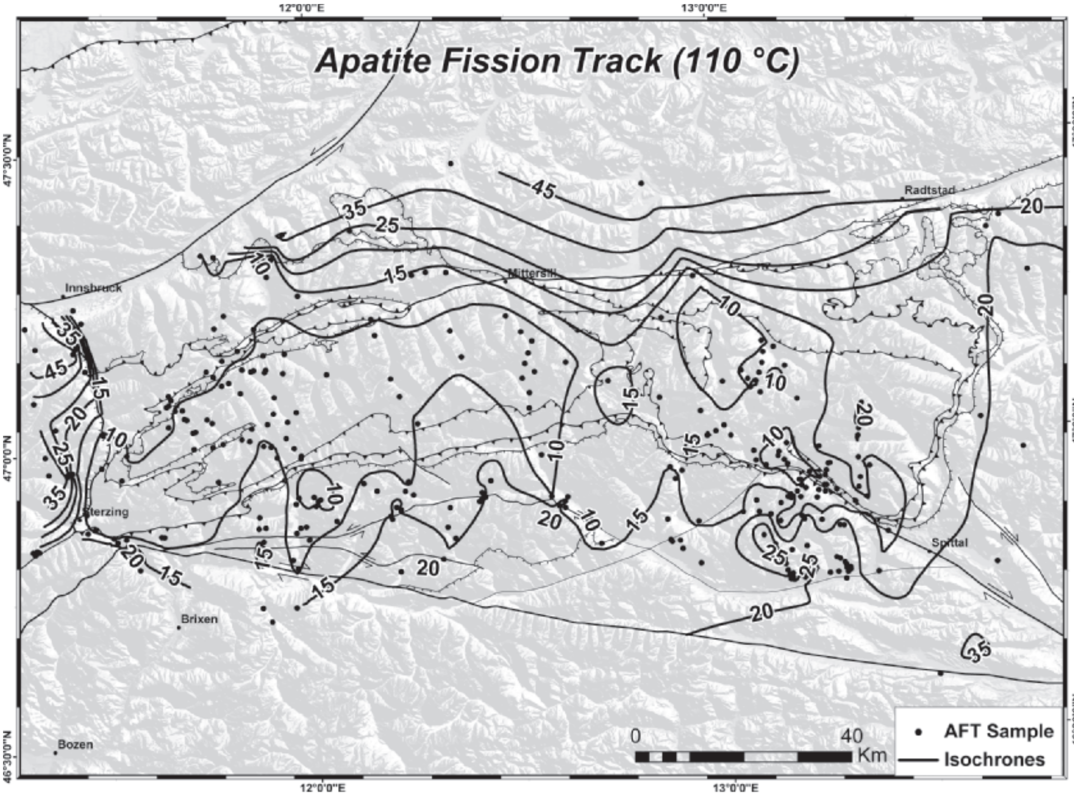


Fig. 3. Isochrone maps for temperatures of 375 (a), 230 (b) and 110 °C (c), respectively. (d) Isochrone map making only use of AFT ages with an altitude range of 1000–2000 m (blue range in histogram) in order to reduce topographic effects. See text for further explanations. Lower right inset shows the frequency of AFT data with respect to altitude. Upper left inset: Engadine Window. Upper right inset: Rechnitz Window. The solid lines represent isochrones and are based on interpolation of the plotted ages. The dashed lines are extended interpretations. Geological boundaries are based on the Structural model of Italy (Bigi, et al. 1990–92).

c


Apatite Fission Track (110 °C)
Innsbruck
Mittersill
Radtstad
Sterzing
Spittal
Brixen
Bozen
AFT Sample
Isochrones
0
40
Km
12°0'0"E
13°0'0"E
47°30'0"N
47°0'0"N
46°30'0"N

d

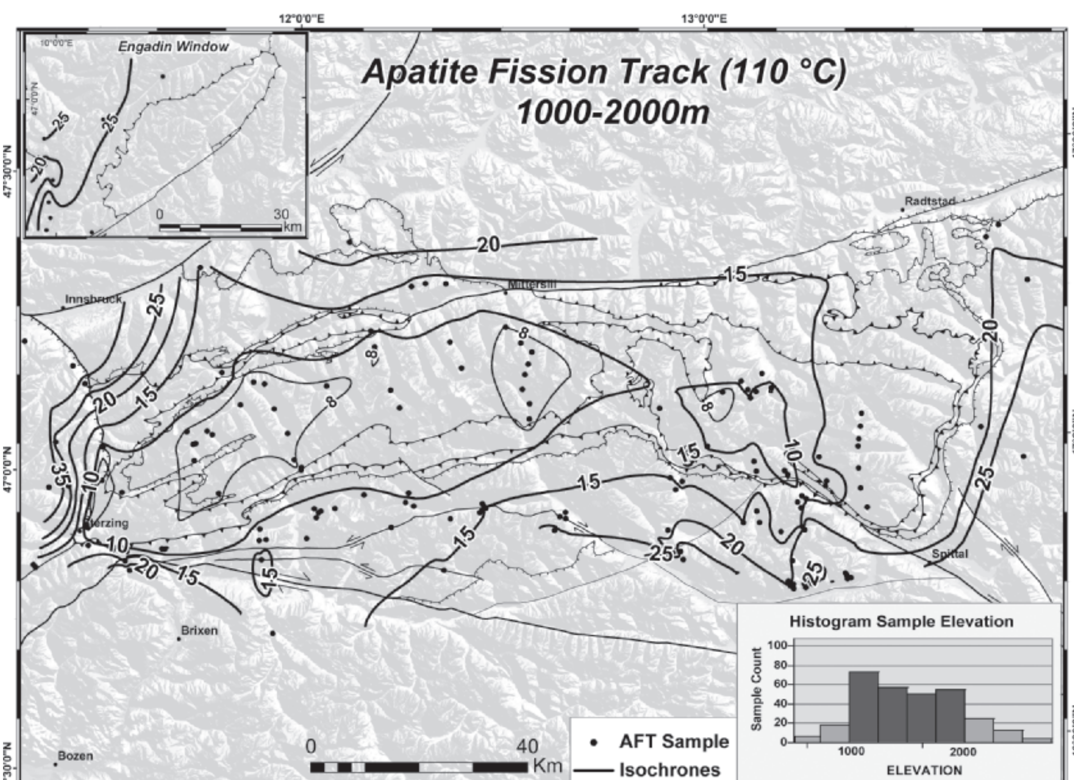
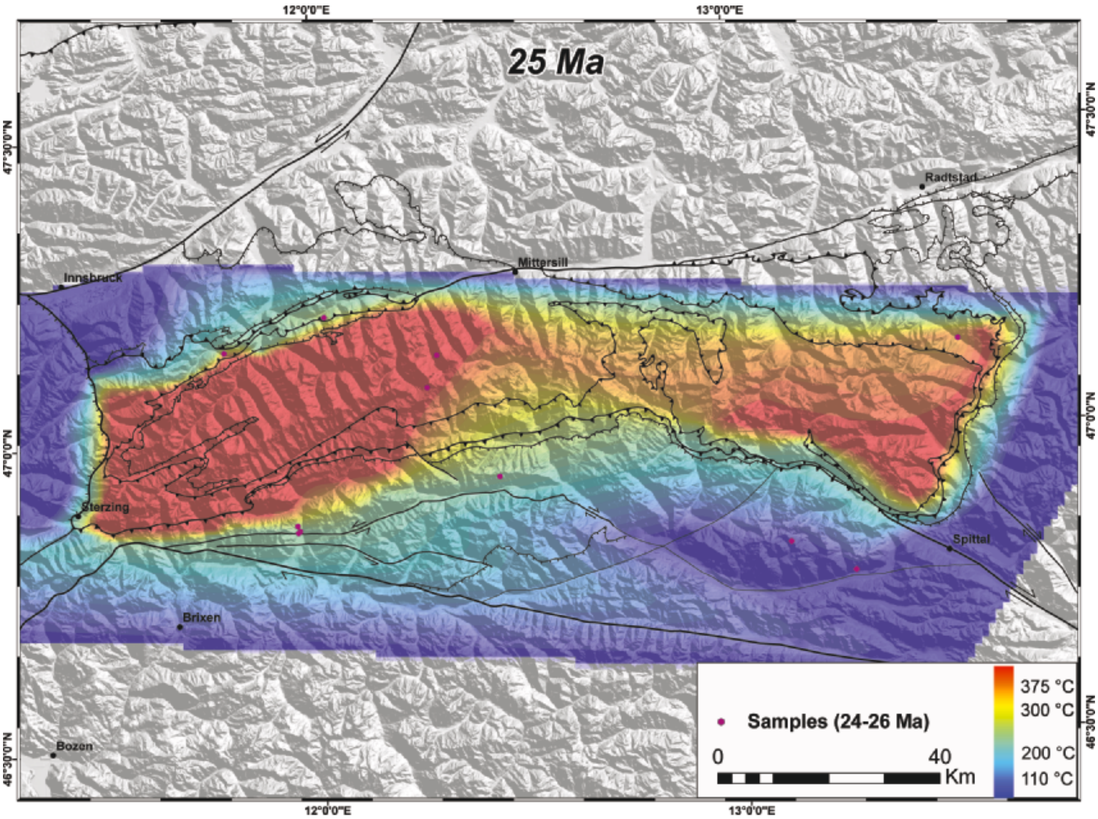

Apatite Fission Track (110 °C)
1000-2000m
Engadin Window
0
30
km
Innsbruck
Mittersill
Radtstad
Sterzing
Spittal
Brixen
Bozen
AFT Sample
Isochrones
0
40
Km
Histogram Sample Elevation
Sample Count
ELEVATION
12°0'0"E
13°0'0"E
47°30'0"N
47°0'0"N
46°30'0"N

Fig. 3. c, d.

a



b

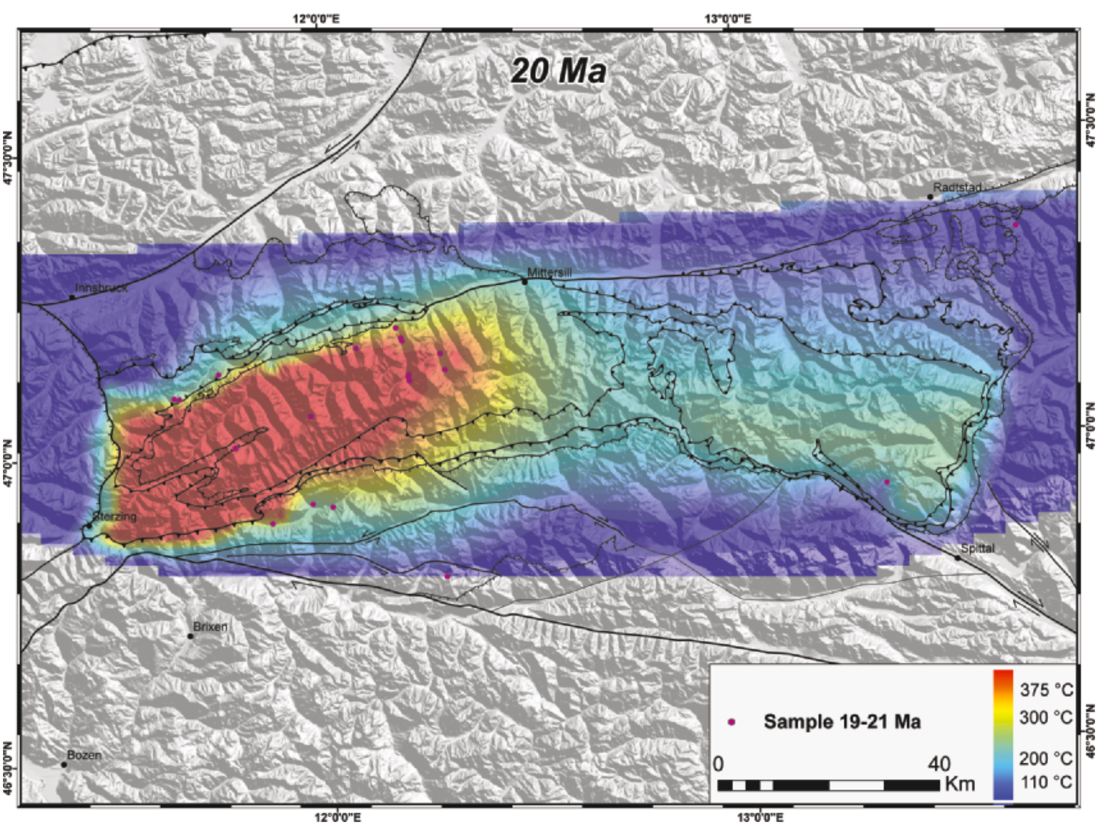
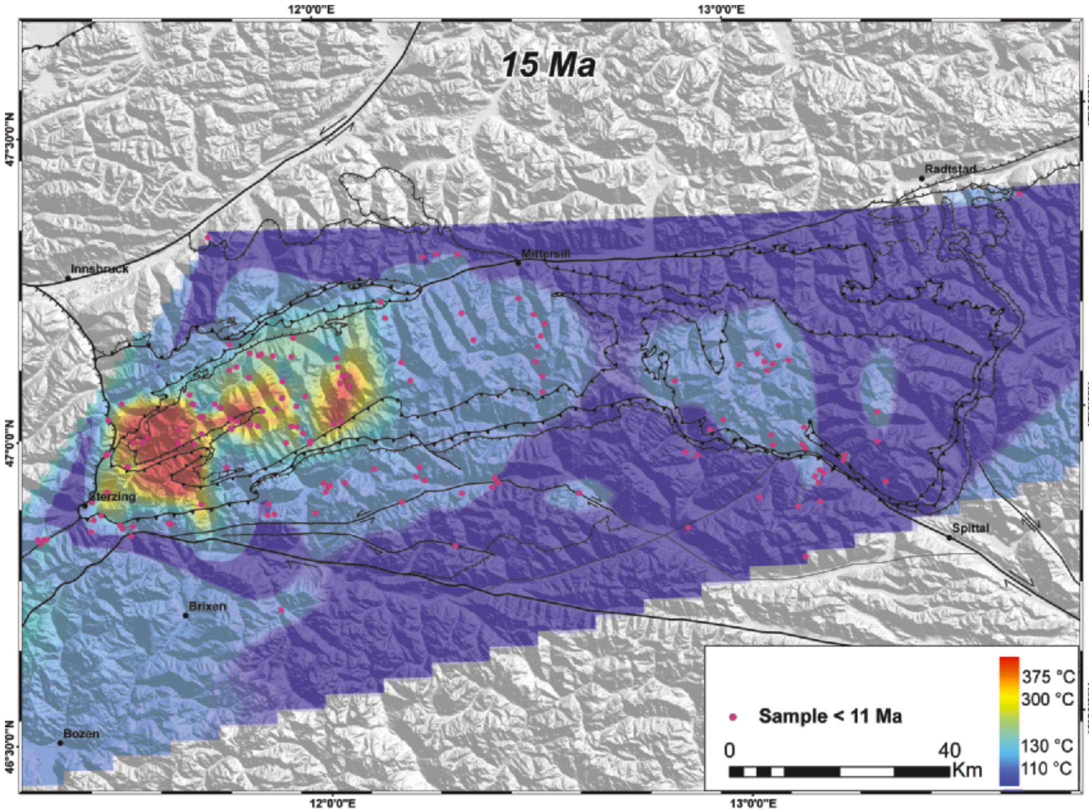


Fig. 4. Temperature maps at 25 (a), 20 (b), 15 (c) and 10 Ma (d), respectively, portraying temperatures, based on the interpolation of cooling age data. The plotted ages together with the time-lines from figure 3 were used as input. Notice the different temperature scale in figure c and d to optimize visualization of low temperatures.

c


15 Ma
12°0'0"E
13°0'0"E
47°30'0"N
47°0'0"N
46°30'0"N
Radstadt
Innsbruck
Mittersill
Sterzing
Spittal
Brixen
Bozen
Sample < 11 Ma
0
40
Km
375 °C
300 °C
130 °C
110 °C

d

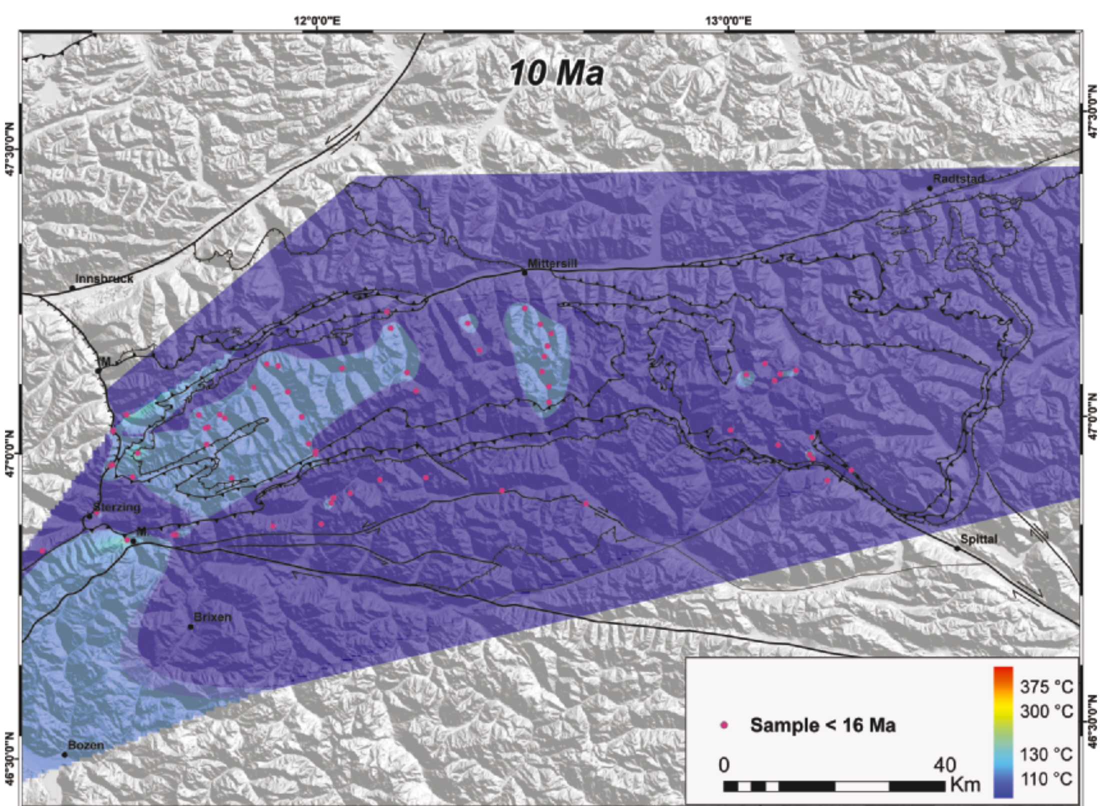

10 Ma
12°0'0"E
13°0'0"E
47°30'0"N
47°0'0"N
46°30'0"N
Radstadt
Innsbruck
Mittersill
Sterzing
Spittal
Brixen
Bozen
Sample < 16 Ma
0
40
Km
375 °C
300 °C
130 °C
110 °C

Fig. 4. c, d.

Both, the 25 and 20 Ma maps reveal an extension of the thermally defined TW towards the DAV. At 15 Ma (Fig. 4c) the AA units and most of the TW had cooled below 110 °C and the highest temperatures are limited to the hinge of the structural antiform of the western TW.

Further cooling through 110 °C at 10 Ma (Fig. 4d) is mainly recorded by AFT samples obtained from valleys or along the antiformal hinge of the western TW. During the entire cooling history high temperature gradients are inferred across the Brenner Line whereas temperature seems to have changed more gradually in the vicinity of its eastern counterpart, the Katschberg Line.

Discussion

General Conditions at the Onset of Post-metamorphic Cooling

Tertiary peak temperature conditions, up to ca. 650 °C, related to widespread greenschist and amphibolite facies metamorphism within the Penninic windows of the Eastern Alps, were reached by the end of early Oligocene (Thöni, 1999 and references therein). This phase of metamorphism is a consequence of Late Eocene to Early Oligocene collision during which parts of the distal European margin, the present-day Penninic units exposed within the Engadin, Tauern and Rechnitz Windows, became part of the orogenic wedge. Since continental basement is only known from the interior of the TW it is assumed that strong lateral gradients (from W to E) in crustal thickness and topography existed by the end of the early Oligocene (Frisch et al. 1998). Following crustal thickening and thermal relaxation, rapid exhumation of the rocks within the TW occurred under isothermal conditions (Droop 1985; Von Blanckenburg et al. 1989; Fügenschuh et al. 1997). Thermal modeling shows that rapid exhumation of rocks has the capacity to advect heat upward and to produce a transient thermal dome, which leads to softening of the rocks (e.g. Genser et al. 1996). Hence, further exhumation of Penninic rocks probably occurred within a weak crust, which responded to geodynamic changes on its eastern boundary, i.e. subduction along the Carpathian arc and back-arc opening of the Pannonian basin by ductile flow within the lower plate Penninc units and by escape of fault-bounded wedges towards the east within the brittle upper plate AA units (Ratschbacher et al. 1991).

The Thermal Tauern Window

Within the Eastern Alps the post-collisional cooling path of most of the Austroalpine units differs significantly from that of the Penninic ones. In the former, cooling below 230 °C starting from a thermal maximum around ~90 Ma occurred mostly before Cenozoic times. Within the Penninic Windows, peak temperature conditions of the latest amphibolite to greenschist facies metamorphism were reached only ~30 Ma ago and were followed by rapid cooling from 500 °C to 110 °C, mainly during the Miocene (e.g. Hoinkes et al, 1999 and references therein).

The exceptions to this general observation are the AA units surrounding the TW. The AA units to the north of the DAV show a Oligocene greenschist facies thermal overprint followed by late Oligocene to Miocene cooling, which is similar to that of the Penninic units in the western TW. This means that no major vertical movements have taken place between the TW and the AA units along the southern margin of the window suggesting that the AA units north of the DAV can be considered as a part of the thermally defined TW (Frisch et al. 2000). The fact that this AA region and the TW share at least part of their tectonic history is also supported by their structural concordant relation with respect to the Oligocene ductile deformation (Krenn et al. 2003). Regional differences in exhumation along the DAV are expressed by Zircon FT (ZFT) ages (25–15 Ma) and K/Ar biotite ages (27–26 Ma) to the north of the fault, and ZFT ages of 34–28 Ma directly south of the DAV (Stöckhert et al. 1999; Most 2003). Furthermore, ZFT ages gradually increase eastwards toward Cretaceous ages, indicating that the western part (of the DAV?) was possibly exhumed from deeper levels, consistent with the deeper intrusion depth of the Rensen with respect to the Rieserferner pluton (Borsi et al. 1978b; Steenken et al. 2002; Krenn et al. 2003). These lateral differences can be explained by lateral variations in amount of shortening, which is highest at the Southalpine indentor tip (Borsi et al. 1978b; Frisch et al. 1998; Most 2003).

Cooling Trends

From the Oligocene onward, the structural boundaries of the TW outline a region of relative younger cooling ages compared to its surrounding Austroalpine units.

Two main cooling trends appear within the TW (Fig. 5):

1) A westward younging towards the Brenner Line, which acts as a major thermal discontinuity, is prevalent in the entire western TW. Termination of the 230 °C isotherms against the Brenner fault reflects fault activity until at least 10 Ma (Fig. 4c). An eastward younging towards the Katschberg Line is not that well constrained but is expected as the Katschberg Fault is a first order fault separating two distinct tectono-thermal domains (Fig. 4a–b) (Genser & Neubauer 1989).
2) A north-south cooling trend with the youngest ages (< 10 Ma) along the central axis of the TW is observed in the western TW, but applies also to low temperature isotope systems in the surrounding Austroalpine units with Paleogene and pre-Cenozoic ages.

The E–W cooling trends, which are parallel to flow and escape kinematics, are in agreement with detachment-related gneiss domes as proposed by Yin (2004) and are observed in several core complex-type structures around the world, (e.g. Nevado-Filabride Core Complex, SE Spain, (Gallagher et al. 1998). In the western Tauern Window, the Brenner normal fault, which probably became active soon after peak metamorphic conditions at 30 Ma (Selverstone et al. 1988), seems to exert a strong

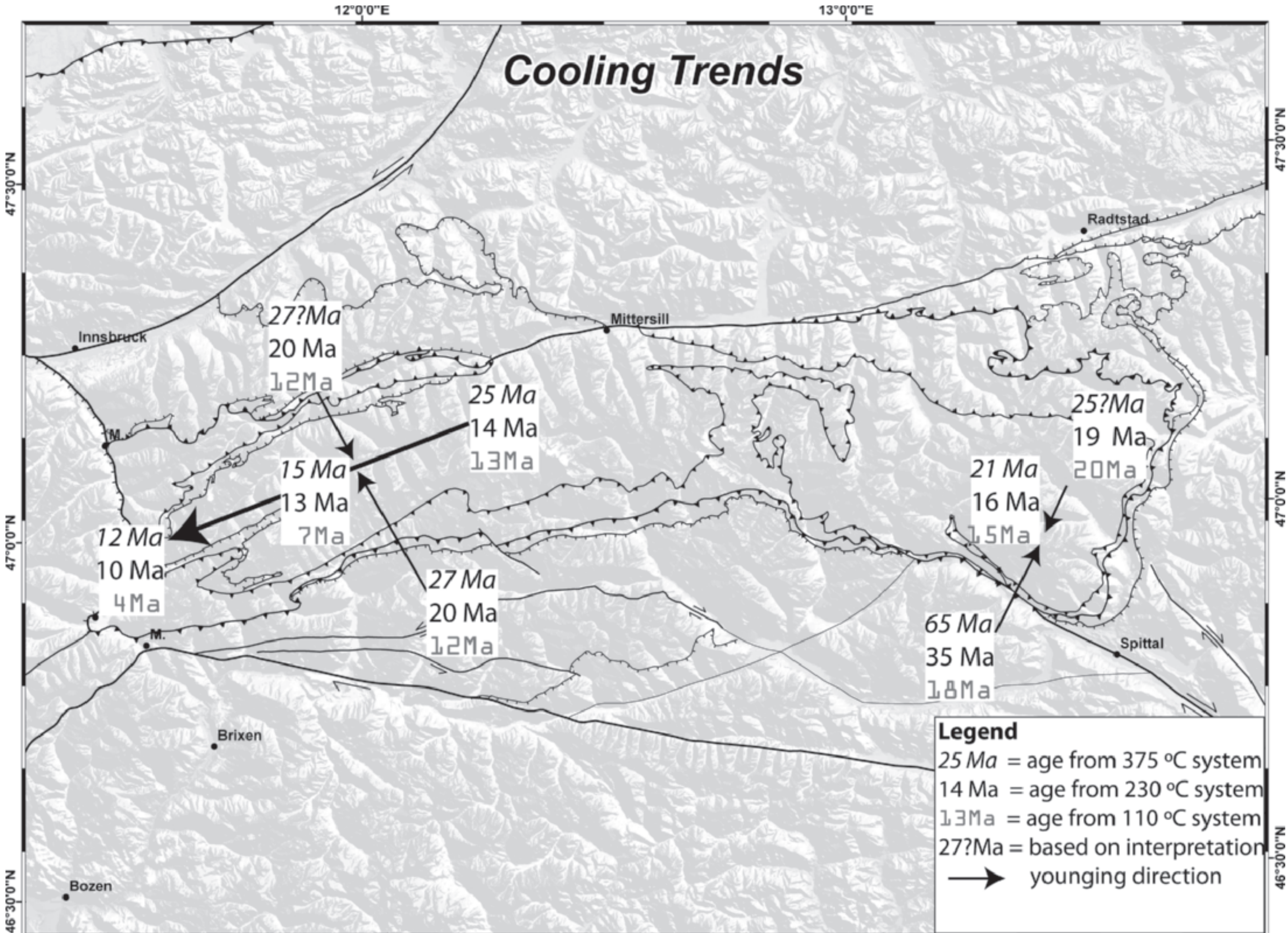


Fig. 5. Different cooling trends deduced from the isochrone and temperature maps (Figs. 3 and 4). Note that both, the Brenner and the Katschberg Lines are major thermal discontinuities during cooling of the Tauern Window.

control on the cooling age distribution (see also Fügenschuh et al. 1997).

The N–S cooling trend, which was already established during the early cooling phase (see Fig. 3a), is probably the result of large-scale folding. As to whether the cooling trend already existed prior to folding or if it is the direct consequence of the folding process is difficult to asses. However, structural relationships seem to favour the latter interpretation since they indicate that the folding process must have commenced prior to the intrusion of early Oligocene dykes, which intruded into a sub-vertical foliation representing the axial plane cleavage to outcrop-scale folds at the southernmost TW (Krenn et al. 2003). According to the age data, which portray the geometry of a thermal dome(s), folding and updoming in the western and central TW possibly continued during the Miocene.

The imprint of both trends within the complete temperature window (375–110 °C) is interpreted to reflect ongoing N–S shortening during exhumation along the low-angle Brenner detachment fault.

Temporal Variations of Post-metamorphic Cooling

The temperature maps portray the presence of two thermal domes within the TW and a pronounced diachronous character of cooling (Fig. 4a–d).

The distinction into two thermal domes may be partly an artefact due to a scarcity of data from the Central TW, but the diachronous cooling is considered as significant since the age difference between the western and eastern TW (2–8 Ma) is beyond the error pertinent to the different dating techniques. As already noticed by Frisch et al. (2000), cooling of the Rechnitz Window and the eastern TW was largely synchronous, whereas cooling in the western TW was delayed by about 5 Ma on average. Frisch et al. (2000) account for this difference by introducing a westerly dipping, normal shear zone within the central TW, which led to the separation of the Zentralgneiss-cored domes of the eastern TW from those of the western TW. Hence, in their model, deformation and subsequent cooling propagated from east to west in response to eastward escape of upper plate brittle crustal wedges and lower plate ductile flow. According to our temperature maps (Fig. 4b), the rocks of the eastern TW were already in a cool environment with temperatures around 230 °C at 20 Ma when lateral extrusion commenced. Sachsenhofer (2001) predicted surface heat flows of up to 200 mWm^{-2} for the eastern TW and easterly adjacent AA units in the main phase of the extrusion process (20–15 Ma) mimicking the geometry of an extrusion corridor (see Fig. 5b of Sachsenhofer (2001)). Heat flow of that magnitude would imply temperatures of 350 °C at depths of about 5 km and the onset of partial melting at depths of ca. 10 km. Such high temperatures in shallow crustal levels should have reset the zircon fission track system to younger ages and this has yet to be documented with data. This suggests that the predicted high heat flow is rather a local, fault-controlled phenomenon than a regional-scale feature.

Diachronous cooling may have been partly conditioned by the crustal configuration prior to orogen-parallel extension in the Eastern Alps since crustal thickness and topographic gradients must have existed at that time not only in N–S but also in E–W direction (see Frisch et al. (1998) for a paleo-topography reconstruction). Consequently heat can be efficiently transferred from the thick and hot regions of the eastern TW to the less thick and cool surrounding AA units. Westerly directed heat transfer in the region of the western TW was probably inefficient due to the lack of significant crustal thickness and topographic variations (high mountainous relief from the Ötztal and Silvretta to the Swiss Alps at ca. 29–22 Ma (Frisch et al.1998).

Cooling Rates

Cooling rates in the TW's interior from 375 °C to 230 °C were high (50 °C/Ma) during the Early Miocene, while cooling towards surface conditions slowed down to 25 °C/Ma in the east at around 15–9 Ma and in the west between 12 and 8 Ma.

In the areas close to the major bounding normal faults, near-surface cooling (from 230 °C to 110 °C) was rapid (~50 °C/Ma) and happened in the eastern TW between 18 and 14 Ma and in the Brenner pass region between 14 and 10 Ma (Fügenschuh et al. 1997).

Fügenschuh et al. (1997) calculated exhumation rates in the western TW with the use of isotope data and a time-dependant thermal model for erosion. Their results suggest that Oligocene to early Miocene rapid exhumation predates late Early-Middle Miocene rapid cooling. Hence, lateral extrusion in the Eastern Alps coincides with a phase of rapid cooling. Exhumation related to lateral extrusion, therefore, was not able to maintain the high temperatures of the isothermal exhumation phase suggesting that vertical motions were already slowing down at that stage of TW formation, as also suggested by the geochronologic data of von Blanckenburg et al. (1989).

Dome Forming Mechanisms for the Tauern Window

Different exhumation mechanisms operate at different rates and time-scales and may be diachrounous in space potentially leaving behind different cooling records (Hames & Bowring 1994). Several mechanisms have been suggested for the exhumation of the TW with the primary distinction between the models in the relative importance of the N–S shortening tectonics (Lammerer & Weger, 1998) with respect to the E–W extensional, extrusion related tectonics (Selverstone & Spear 1985; Ratschbacher et al. 1991; Frisch et al. 1998, 2000).

Lammerer and Weger (1998) argue, based on strain measurements, that north-south shortening continued during east-west extension and they conclude that shortening was compensated by extension and, therefore, would not have caused substantial uplift of the TW. In their view the Tauern Window is merely a deeply eroded antiformal stack, which experienced crustal-scale folding. A reduction of crustal strength (Genser et al. 1996) as a consequence of thermal relaxation and early phases of exhumation could have favoured crustal-scale buckling and uplift.

On several accounts it has been suggested that the TW is a metamorphic core-complex (e.g. Frisch et al. 1998, 2000). With reference to classical metamorphic core complexes as described in the Basin and Range province (Lister & Davis 1989) observations in favour of metamorphic core complex interpretation include: (1) the presence of detachment faults separating brittle upper plate from ductile lower plate rocks; (2) a considerable amount of extension within the core of the TW (E–W), and (3) a lateral decrease of cooling ages towards the main detachment faults (Brenner and Katschberg Lines). However, in Basin and Range-type core complexes the kinematics of the main detachments is uni-directional, which is also documented by uni-directional cooling of the exhumed rocks (e.g. (Foster & John 1999). The early deformation history of both bounding normal faults in the Eastern Alps is still poorly understood and additional research with the focus on the relation between the Brenner Line and the Katschberg Line is needed. Furthermore, Cordilleran-type core complexes are characterised by detachments striking parallel to the mountain range (orthogonal in the Eastern Alps) and their formation post-dates shortening (coeval in the Eastern Alps). Consequently, the TW exhibits a large amount of overprinting relations between extensional and contractional structures.

The elliptical cooling pattern in the TW and close surroundings does not support a Basin and Range-type core-complex origin of the TW but argues for its formation as a syn-orogenic metamorphic dome, which was exhumed by a combination of extension and erosion. Uncertainties remain as to whether the entire TW is a single metamorphic dome or a series of domes.

From Regional to Orogen-scale Exhumation and Cooling

Higher temperature isotope systems (Fig. 3a), as well as most of the zircon fission track data (Fig. 3b), document focused cooling and exhumation confined to the Penninic tectonic windows, whereas the main body of the surrounding AA units already cooled to near surface conditions prior to ca. 20 Ma (e.g. Hejl 1997, Fügenschuh et al. 1997, 2000). Cooling through the AFT annealing zone was nearly coeval along the Brenner fault (Fügenschuh et al. 1997), the central axes of the TW (Grundmann & Morteani1985; Staufenberg 1987; Most 2003), the Jaufen, Passeier and Giudicarie faults (Viola et al. 2001), and the Valsugana thrust system (Zattin et al. 2006), arguing for orogen-scale cooling and exhumation since ca. 12 Ma. Late middle Miocene thrusting and uplift within the Southern Alps, also documented by structural and stratigraphic data (Dunkl & Demeny 1997; Castellarin & Cantelli 2000), were coeval with the termination of extrusion tectonics in the Eastern Alps. This mutual relationship indicates that the coupling between the Southern Alps and the internal part of the Alps (the Alps north of the Periadriatic Line) increased, leading to orogen-scale uplift and cooling to near-surface conditions starting at around 12–10 Ma. Large-scale uplift led to an increase in the catchment area and hence to enhanced sediment discharge compared to the main phase of lateral extrusion (Kuhlemann et al. 2001). Other processes, which possibly contributed to the final widespread uplift stage most likely involve a combination of removal of the lithospheric root either by delamination or convection and surface erosion (Genser et al. 2007).

Conclusion

The compilation of radiometric data and their presentation in "time" and "temperature" maps allow for interpretation of temporal and spatial variations of post-metamorphic cooling within the Eastern Alps.

Based on available isotope data, we argue that the "thermal" differentiation between the western and eastern TW was well established by the end of the rapid, nearly isothermal exhumation phase during the Oligocene (ca. 30–23 Ma). This phase of deformation probably led to the separation of the Zentralgneiss cores, now exposed in the western and eastern TW, in response to orogen parallel extension (e.g. Frisch et al. 2000) and is the main reason for diachronous cooling of the TW. As a result, two thermal domes developed within the TW as documented by an increase of cooling ages away from the centre of the domes. Subsequent decay of the thermal domes was synchronous with the main phase of lateral extrusion in the Eastern Alps, which lasted from ca. 20 to 14 Ma. Hence, cooling by heat conduction and possibly also by convecting fluids dominated over exhumation related upward advection of heat, arguing for a decrease of exhumation rates during that period as suggested by von Blanckenburg et al. (1989).

While N–S cooling trends possibly reflect folding and updoming within a N–S convergent setting, E–W cooling trends appear to be fault controlled, reflecting top-to-the-W and top-to-the-E normal displacement along the Brenner and Katschberg faults respectively. This cooling pattern is consistent with cooling of detachment-related gneiss domes e.g. (Yin 2004), but differs from uni-directional cooling of Basin and Range-type core complexes.

Orogen-scale uplift involving the Southern Alps post-dates the main phase of lateral extrusion and is documented by late Miocene apatite fission track ages from the Southern Alps, the AA unit and the TW. These data possibly reflect increased coupling between the Eastern and Southern Alps across the Periadriatic Line leading to orogen-scale uplift and erosion in the Alps.

Our synthesis of available isotope data also highlighted that more data are needed from the central and north-eastern TW and across the Katschberg normal fault. In particular, a denser network of (U-Th)/He data is required to be able to link Late Miocene to more recent tectonics (Willingshofer & Cloetingh 2003) of the Eastern Alps. Furthermore, a thorough understanding of the cooling history of the Alps and associated vertical movements should invoke a stronger coupling to the dynamics of the mantle lithosphere.

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